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Enhanced Coupling Structures for Wireless Power Transfer Using the Circuit Approach and the Effective Medium Constants (Metamaterials)

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South Korea

1. Introduction

Looking around you in your study or office, you will see electronic goods such as a desktop computer and a printer have wires and power cables tangled and plugged. The power line of your phone is one of a bundle of the lines that make the space on and under your table messy.



Fig. 1. Cables messing the space under your desk in the office.

If the office is shared by more than two workers and their desks are located close to one another, the floor and your leg-rooms are populated by a lot of power lines for the computers and fax machines. Though they are the last thing to show formal visitors, we can't do without them for our work. This might have motivated people to imagine the

cordless PCs and electronic devices that are still empowered by electric energy from the power outlet. Especially, considering wireless communication systems and remote controlled home appliances we use, it might not be very challenging to seek the solutions of the wireless power transmission and reception[1,2]. It is possible to transmit the electric power to a receiving electronic product using the conventional RF technologies, but it is noticed that the way of characterizing and designing a WPT system is not exactly the same as that of linking mobile devices, since the frequency ranges are different. When RF communication systems and WPT components exist together, the design will get more complicated than the purely WPT case? Here is a picture of this situation.

Customarily, the WPT design is done independent of the wireless communication, but Fig. 2 is the right picture that makes us prepared for the near future having the antennas of a laptop and LED communication circuitry. In this chapter, the electromagnetic interference between WPT and RF parts is ruled out for the sake of convenience. Prior to the explanation on the design approaches, we need to look back upon what kinds of techniques have been suggested to couple a transmitter and a receiver in a WPT system. Generally, there are magnetically coupled resonators for short distance WPT system.

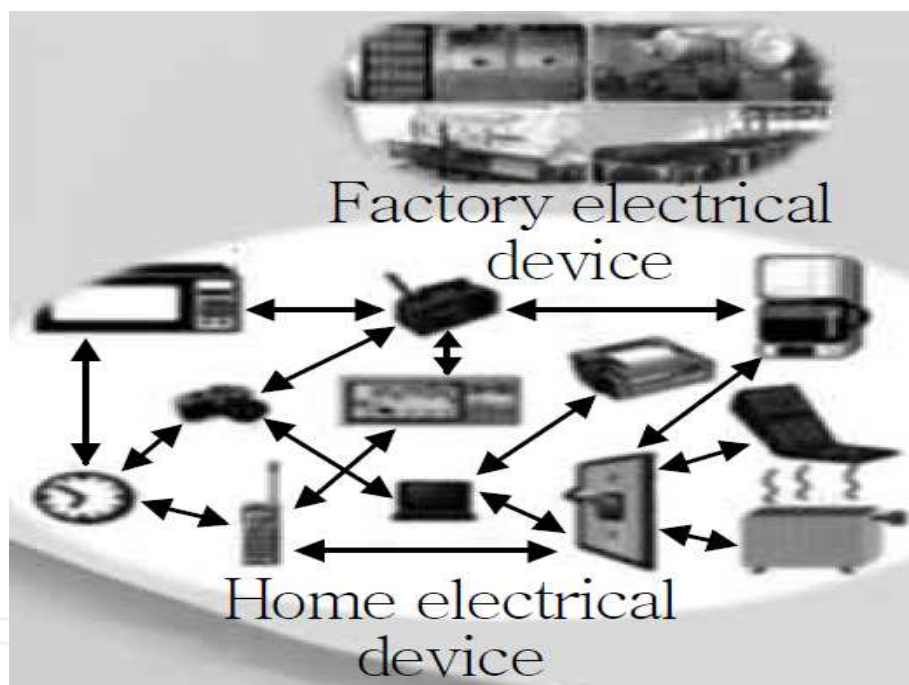


Fig. 2. WPT for home appliances and factory facility[2]

Fig. 3 is a test set-up for WPT. Seen in textbooks on circuit and Electromagnetics, the magnetic field created by the electric current of the transmitter(or loop 1) reaches the receiver(or loop 2) and induces the electric current. This is the product of so called electromotive force Faraday investigated. Actually, since the electric current is alternating current(or AC), it results in electromagnetic fields and radiation, but the frequency of the current is low and the distance between them makes magnetic field stronger than radiated fields and waves. The intensity of the magnetic induction is affected by the radius of a loop and the number of loops(or turns), but the total length of the metallic wire does not determine the frequency. And it is very reactive. However, what if the wire resonates at the frequency of operation to increase the quality factor of the energy transfer?

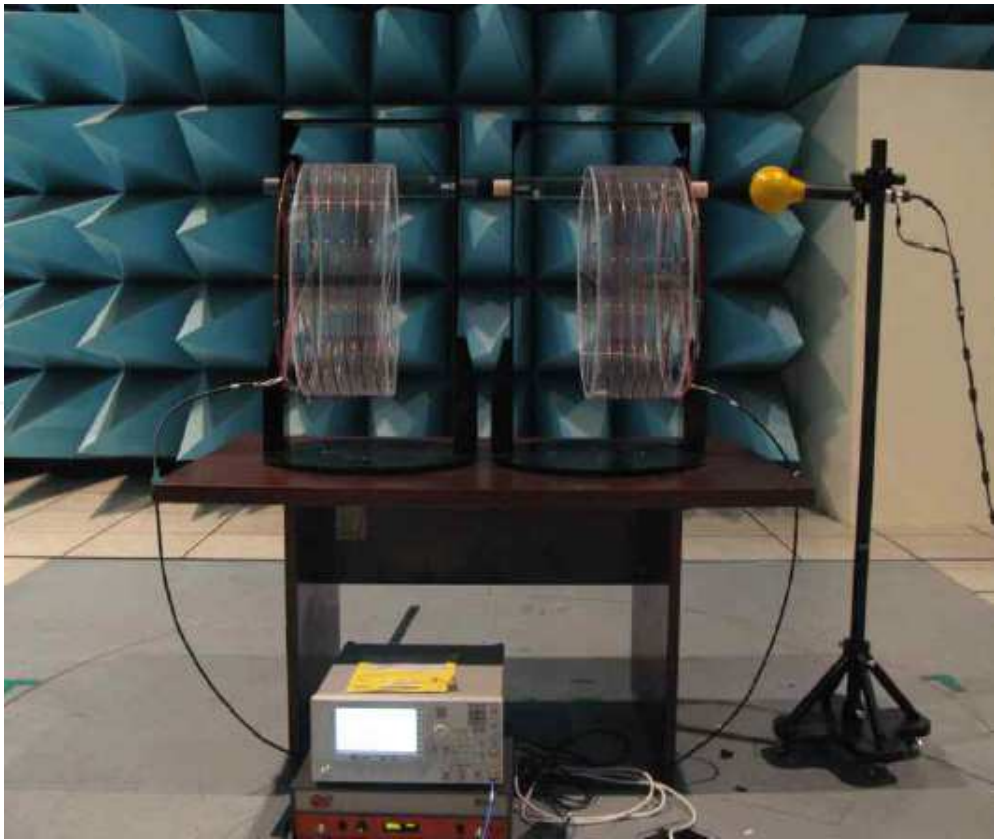


Fig. 3. WPT tested in a semi-anechoic chamber[2].

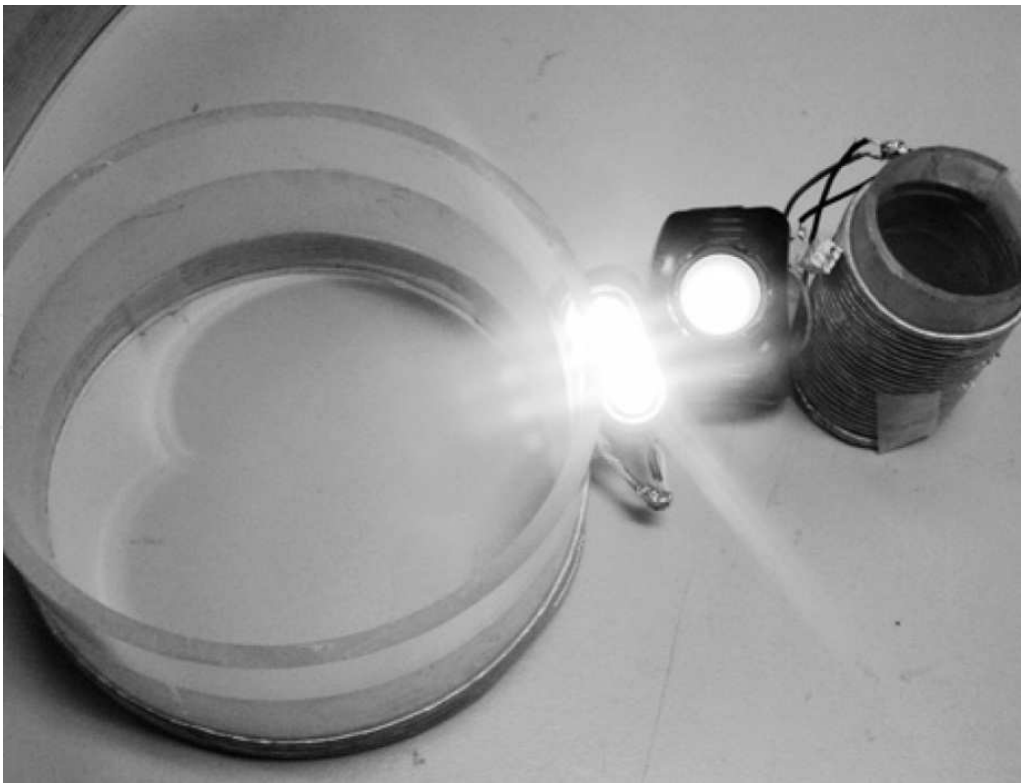


Fig. 4. Resonant loops are used in the university of Incheon. WPT system.

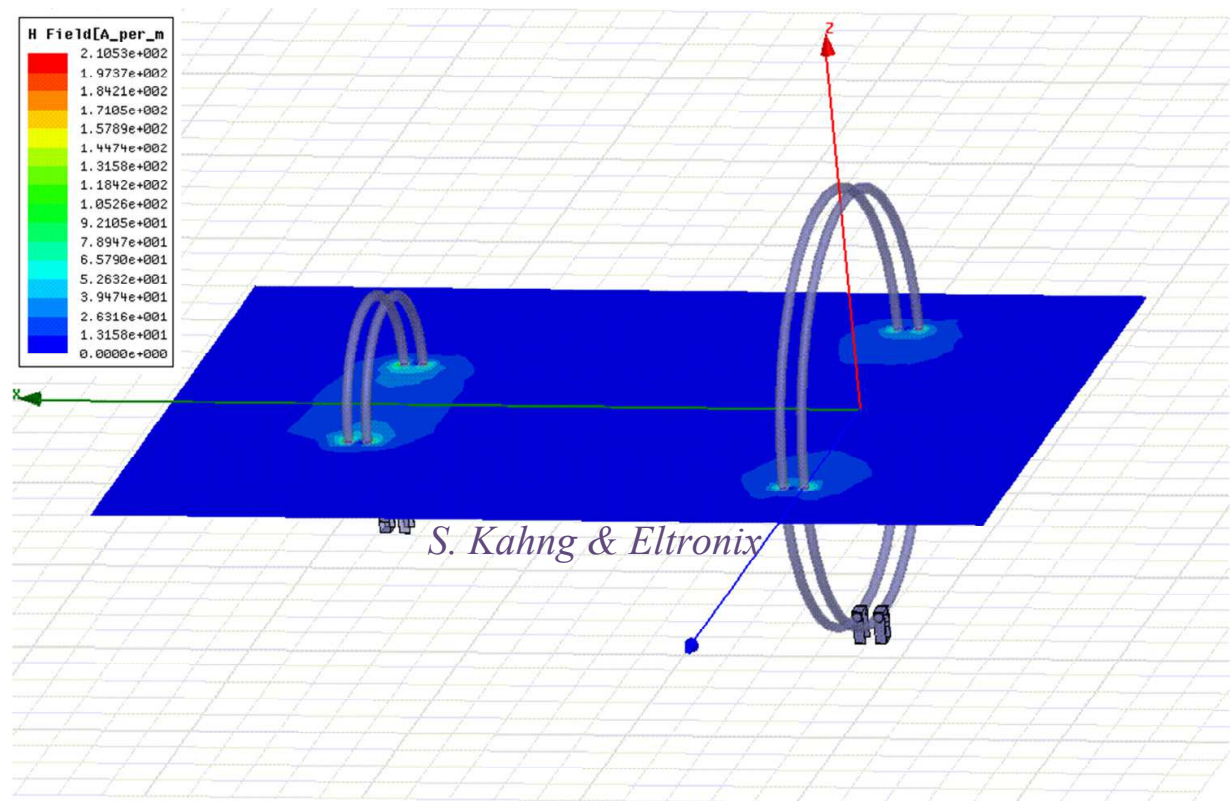
From the experience of RFID system designs, magnetic coupling has a short range, but antennas as resonators of a reader and a tag have a higher coupling value at an increased distance[3]. Magnetic resonators(electromagnetic resonance is correct) or resonant loops are installed for a 60W power transfer experiment with a 2m distance in the figure above. So this chapter describes the design approaches for the resonance type of WPT. The next section is assigned to the circuit approach which is followed by the full-wave simulation iterative design.

2. Brief introduction to the circuit theory approach for the WPT system design

The metallic loops and the field play the roles of resonators and coupling elements in a filter system. This is why the circuit theory can be adopted. The following structure is interpreted as resonators coupled each other and ports.

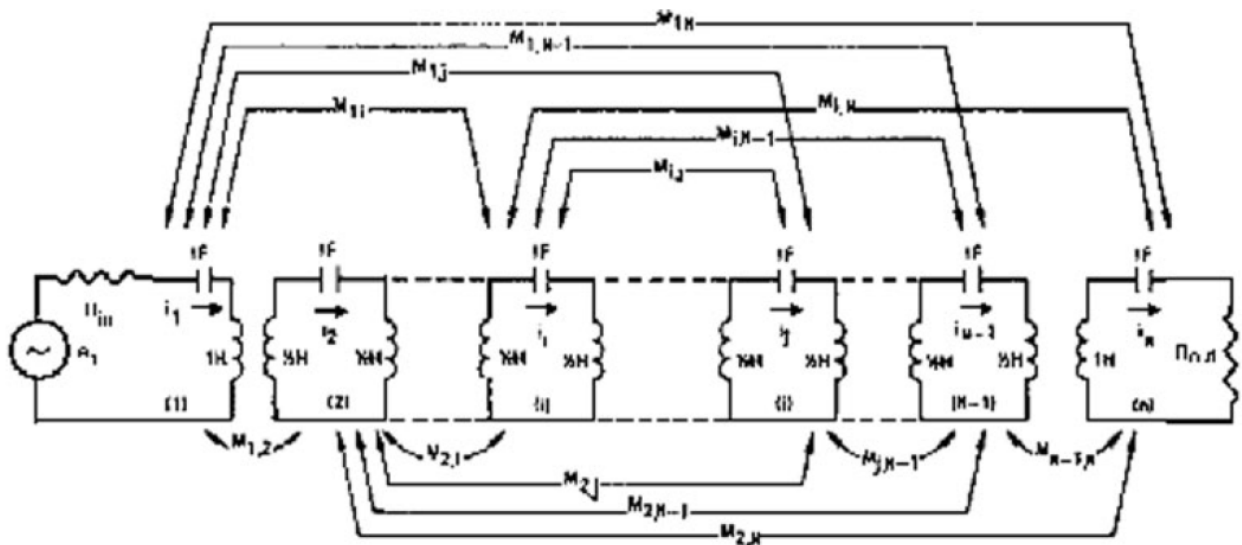
Using the quasi-static formulae shown in the textbooks of Electromagnetics, RFID design handbook or what not[3-5], the geometry results in the circuit elements of its equivalent circuit model that helps designers know the input impedance[6].

The details of the same approach will be revisited in other chapters by H. Hirayama and M. Mongiardo et al of this book. About Fig. 5(a), we check the coupling from the transmitter to the receiver as in Fig. 6. The resonance frequency of the WPT is 13.56MHz and the size of the receiver is less than 10cm×10cm.



(a) Real geometry of theWPT system

Fig. 5. (Continued)



(b) Circuit diagram of a WPT system

Fig. 5. WPT system is interpreted as coupled resonators.

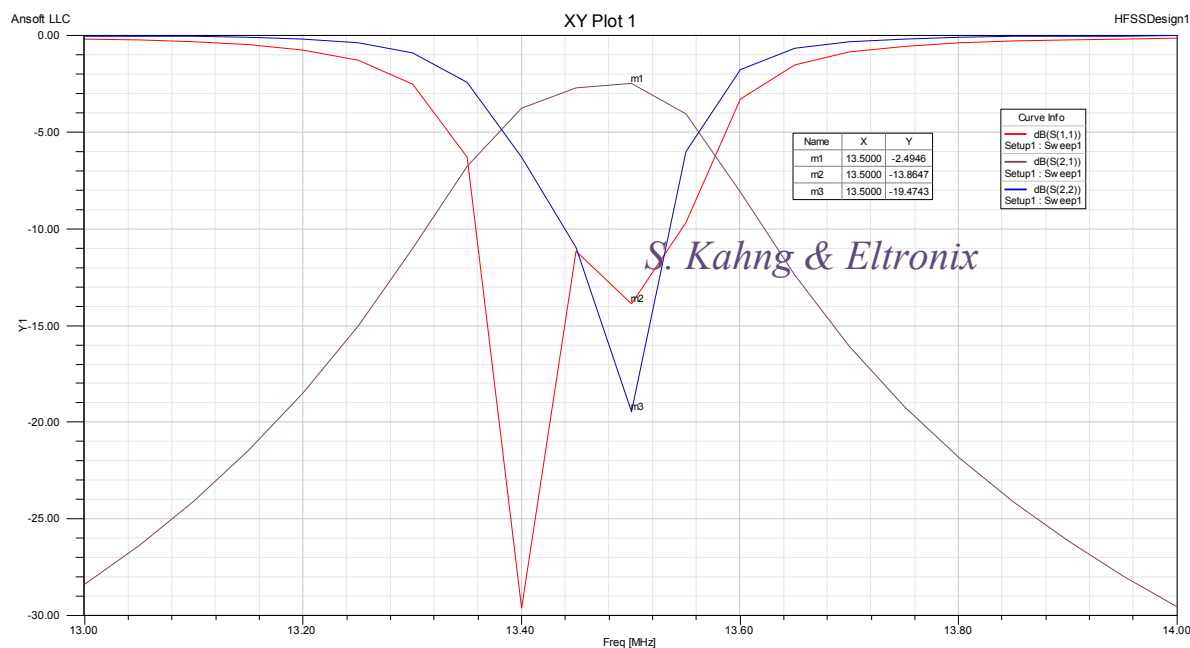


Fig. 6. An indirect-fed example obtained by the present authors.

3. RFID-antenna-inspired full-wave simulation approach and new MTM resonators

Though the near-field RFID and WPT have different purposes and frequencies, it is not too difficult to find something in common to the two areas. They use similar styles of resonance and impedance matching in the near-field zone linkage, and the same formulae of self- and mutual loop inductance. So in this section, the resonance frequency is set as 900MHz, and the full-wave solution approach adopted in the RFID antenna design is used, and a new

concept metamaterial loop resoantor to increase the transfer coefficient with no change in the size is presented. Please note the full-wave solver is the FIT method where the size of a mesh is 1 tenth of wavelegth and the 8 layered PML is used as the absorbing boundary condition. First, an ordinary resonant loop is desinged(as a transmitter or a receiver).

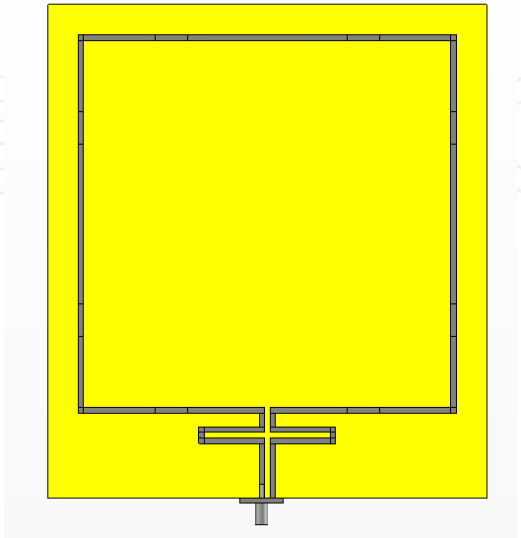


Fig. 7. A conventional rectangular resonant loop.

As this is an ordinary rectangular loop, it has multiple resonances as the harmonics above the first resonance.

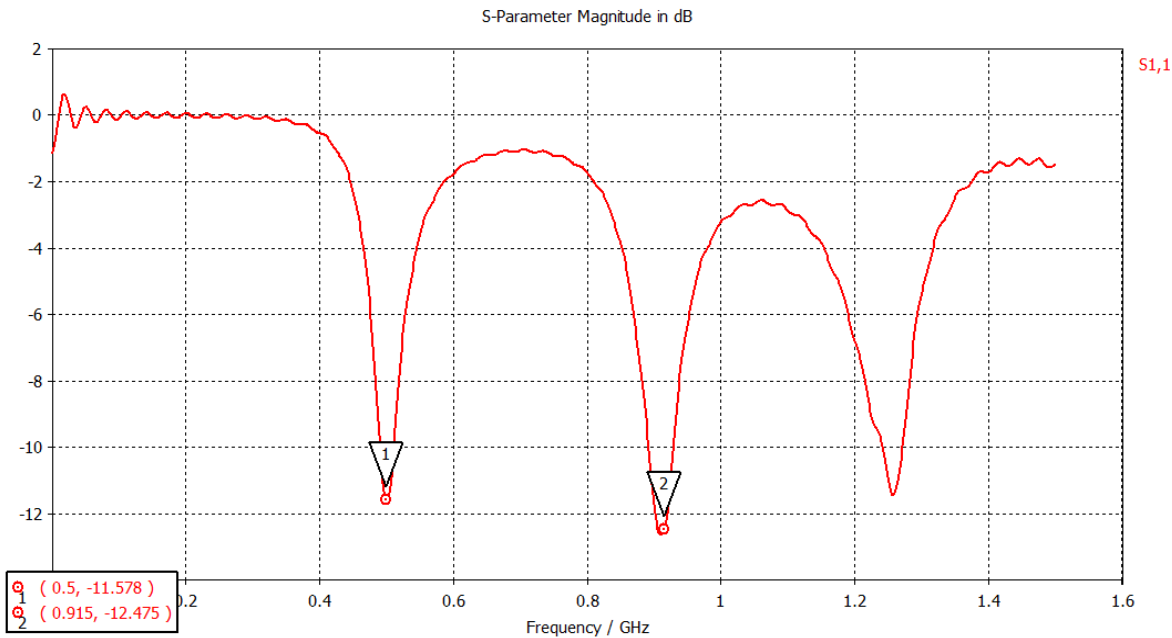


Fig. 8. Return loss(or S_{11}) of the conventional rectangular resonant loop.

The resonance at 900MHz shows the best impedance match from the figure above. So the frequency is used to couple the power source to the power load. We have plotted the he magnetic field distribution at a near-field distance over the ordinary resonant loop.

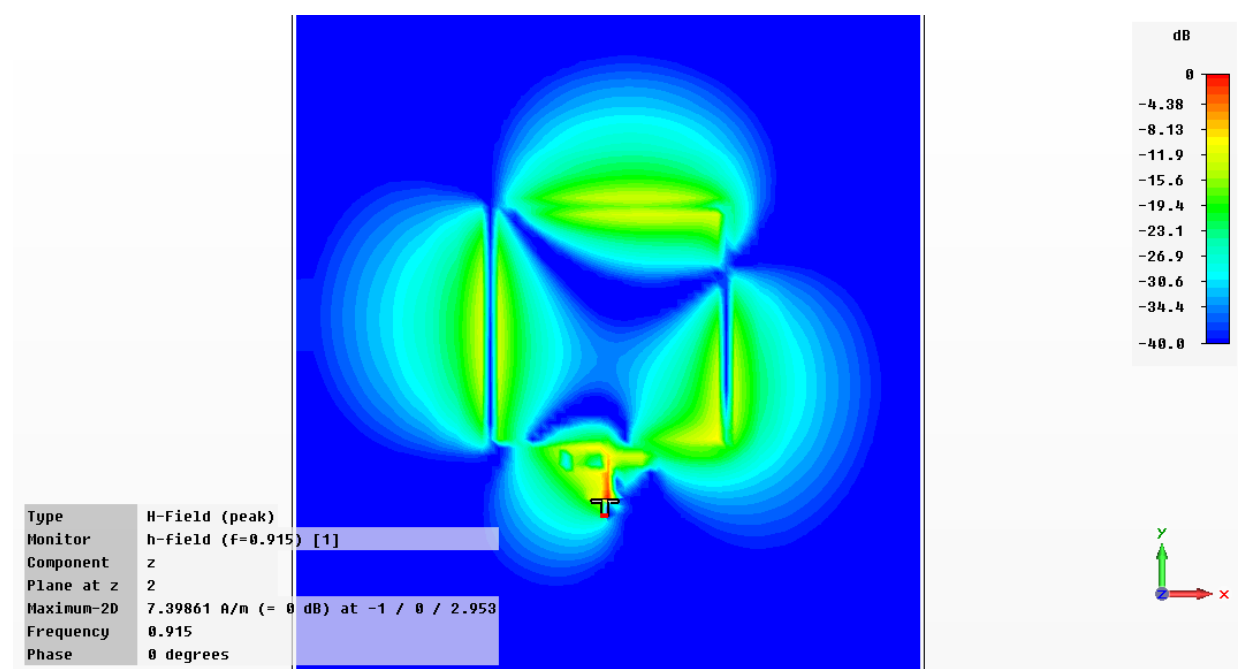


Fig. 9. Magnetic field distribution in the vicinity of the conventional rectangular resonant loop.

Because the standing waves of half-wavelength and its interger multiples are created along the loop at resonances, we can see several null points through which the direction of electric currents changes. Due to this fact, the magnetic field has weak points fromed around the central axis of the inside of the loop. Using the loop, we can check the transfer coefficient of the WPT with different distances. The following set-up has the two ordinary resonant loops placed with a 5cm-distance.

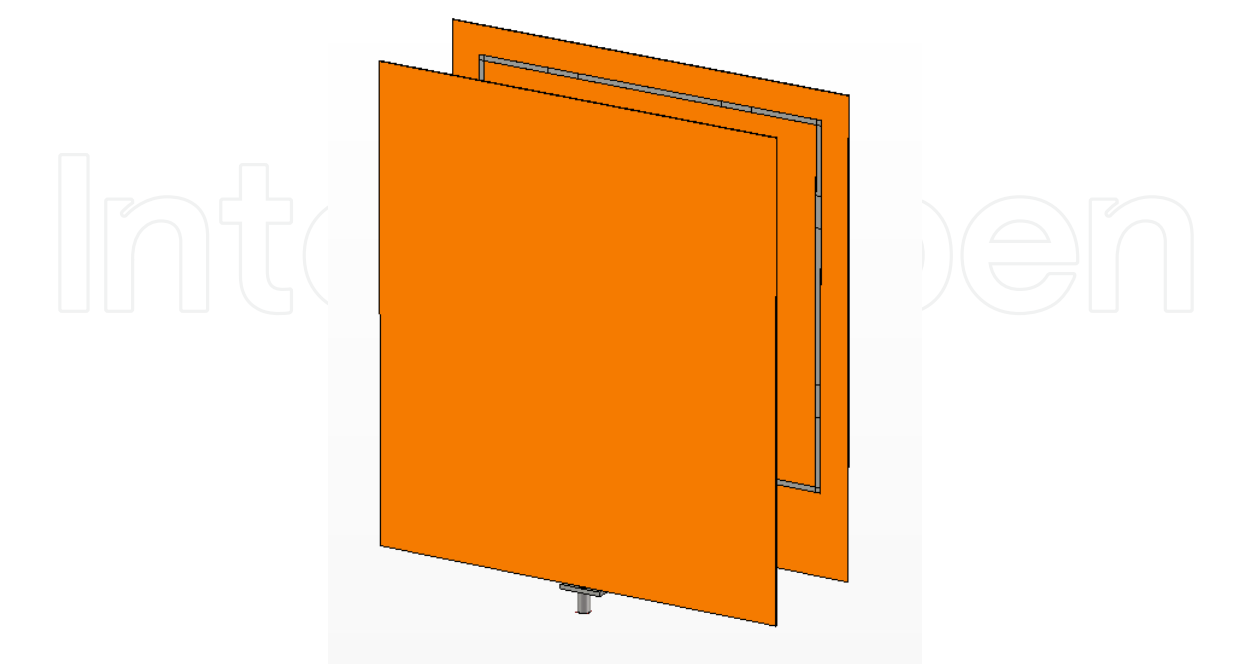


Fig. 10. The two ordinary resonant loops are 5cm away.

Though their distance is very short and impedance mismatch occurs, the original loops are neither modified nor tuned for the best condition, for the sake of convenience. Its S_{21} as the transfer coefficient is calculated as

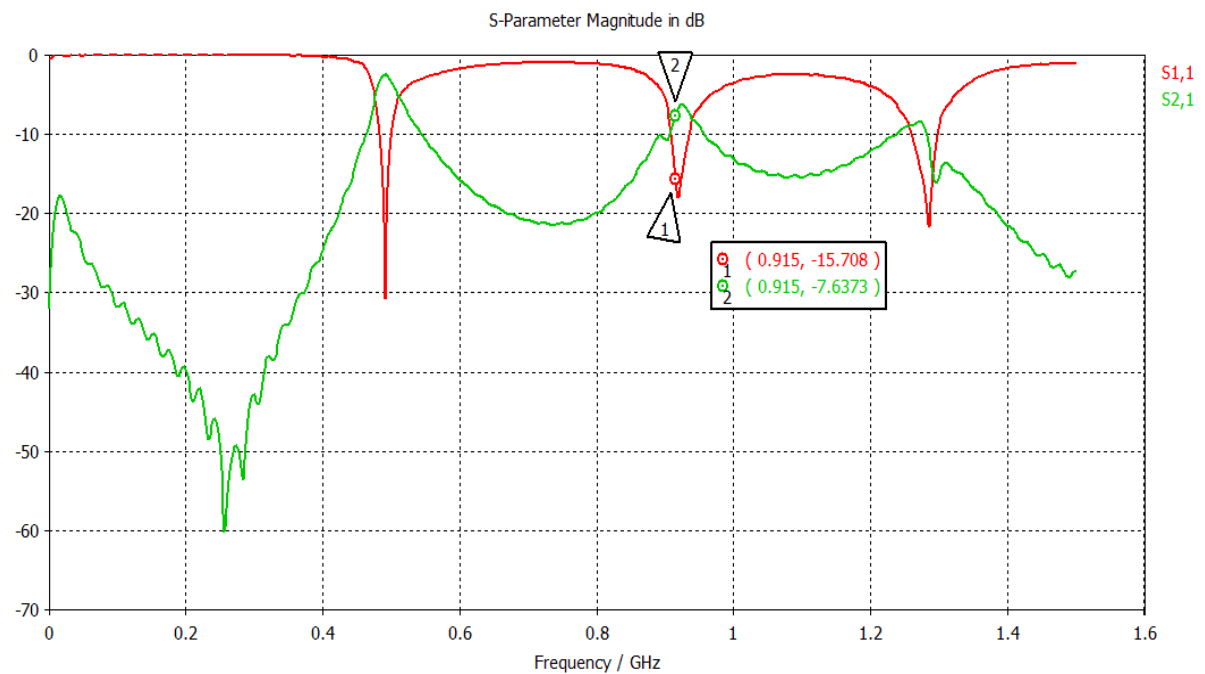


Fig. 11. S_{21} when the two ordinary resonant loops are 5cm away.

S_{21} at 900MHz is read -7dB with the unchanged loops in a changed environment. Next, the distance between the conventional rectangular resonant loops becomes 10cm. Still, the frequency of 900MHz is observed.

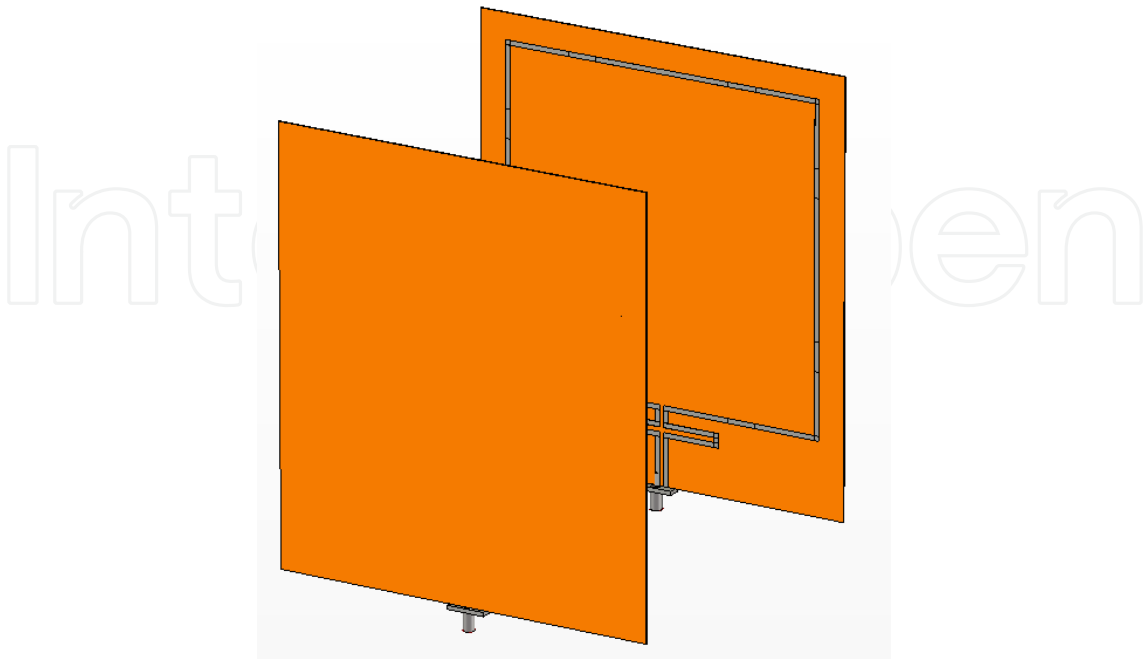


Fig. 12. The two ordinary resonant loops are 10cm away.

Though their distance is still very short and the impedance of the loop is mismatched, the original loops are neither modified nor tuned for the best condition, for convenience. Its S_{21} as the transfer coefficient is calculated as

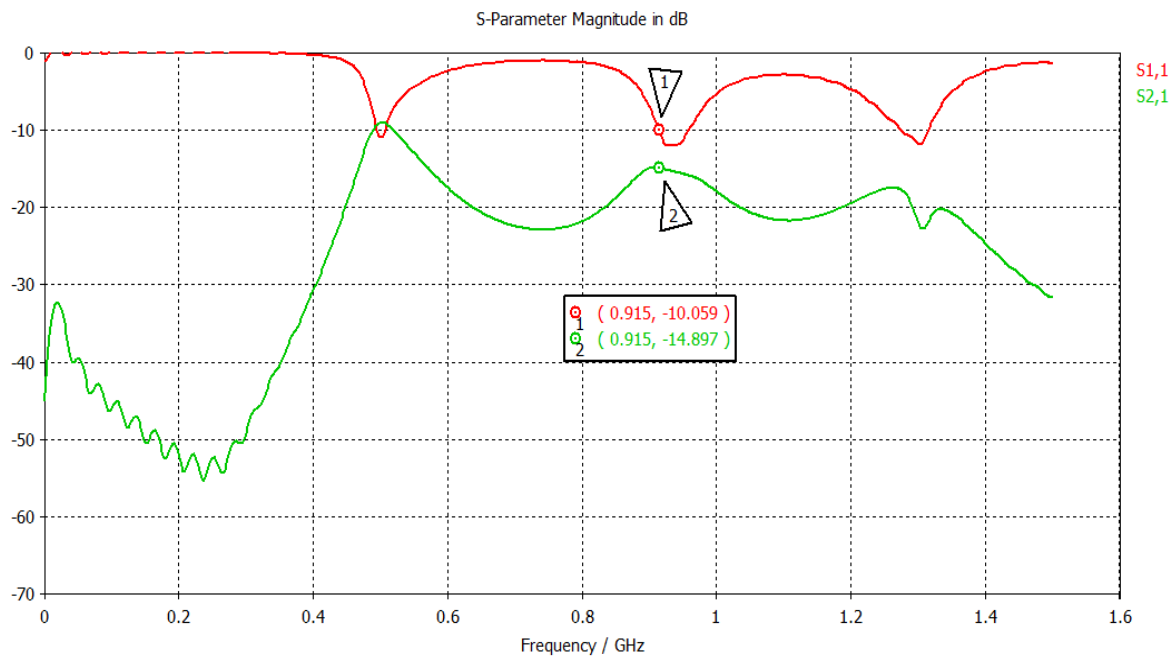


Fig. 13. S_{21} when the two ordinary resonant loops are 10cm away.

S_{21} at 900MHz is read -15dB with the unchanged loops in a changed environment. The transfer coefficient has dropped by 8dB according to the increased distance. Next, the conventional rectangular resonant loops are placed with the distance of 25cm. The frequency of 900MHz is still observed.

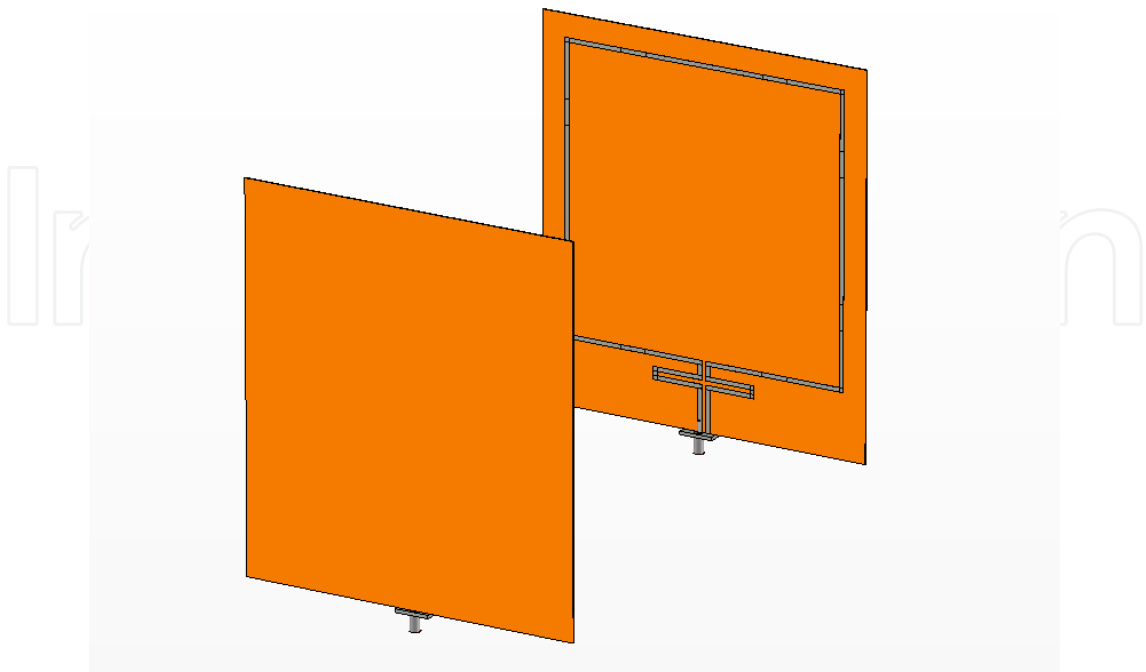


Fig. 14. The two ordinary resonant loops are 25cm away.

While their distance has increased and the impedance mismatch of the loop has got mitigated compared to the former two cases, the original loops are neither modified nor tuned for the best condition, for convenience. Its S_{21} as the transfer coefficient is calculated as

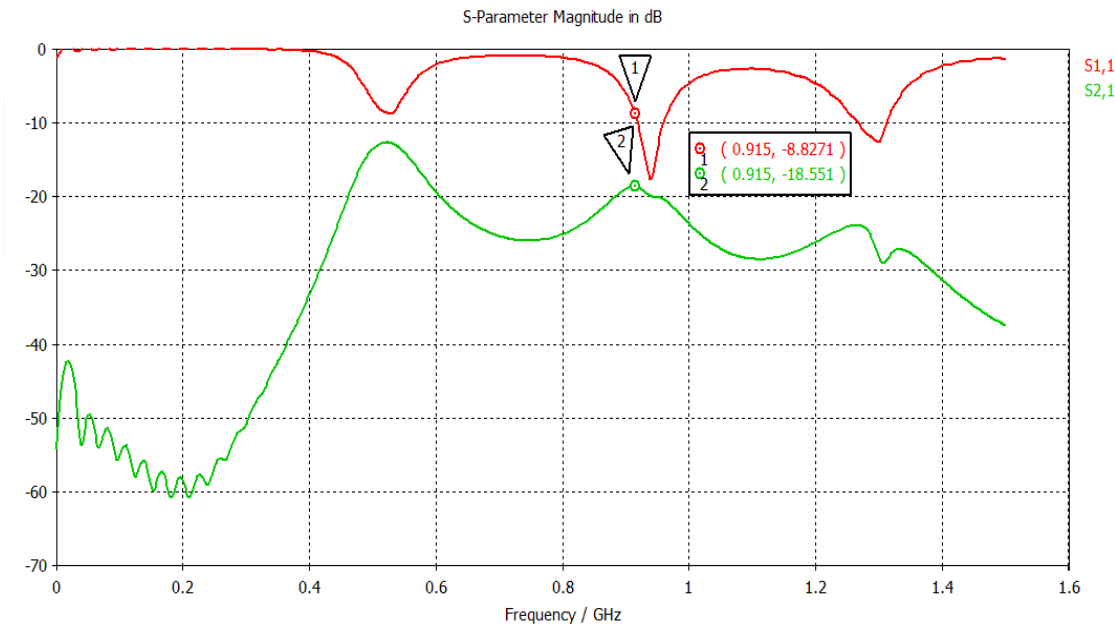


Fig. 15. S_{21} when the tow ordinary resonant loops are 25cm away.

S_{21} at 900MHz is read -18dB with the unchanged loops in a changed environment. The transfer coefficient has dropped by 11dB from the distance of 5cm. It is inferred that the increased distance can be a reason to experience the degraded transfer efficiency along with the impedance mismatch due to the fixed geometry of the loops and a relatively high frequency. Another reason of the weakened coupling is that the ordinary resonant loop can't get the maximum value of the magnetic field along the center axis. The magnetic field in the axis determines the coupling and efficiency between the transmitter and receiver. So by devising a metamaterial ZOR loop hinted from [7-9], we would like to create the the maximum value of the magnetic field along the center axis with no change in the size of the loop and can improve the WPT coupling.

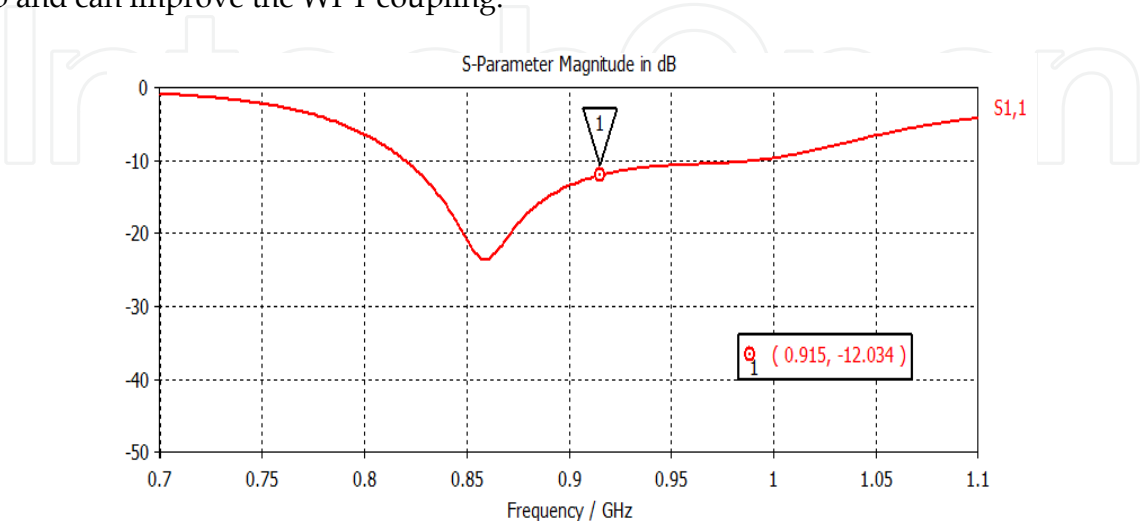


Fig. 16. Return loss of the metamaterial ZOR loop.

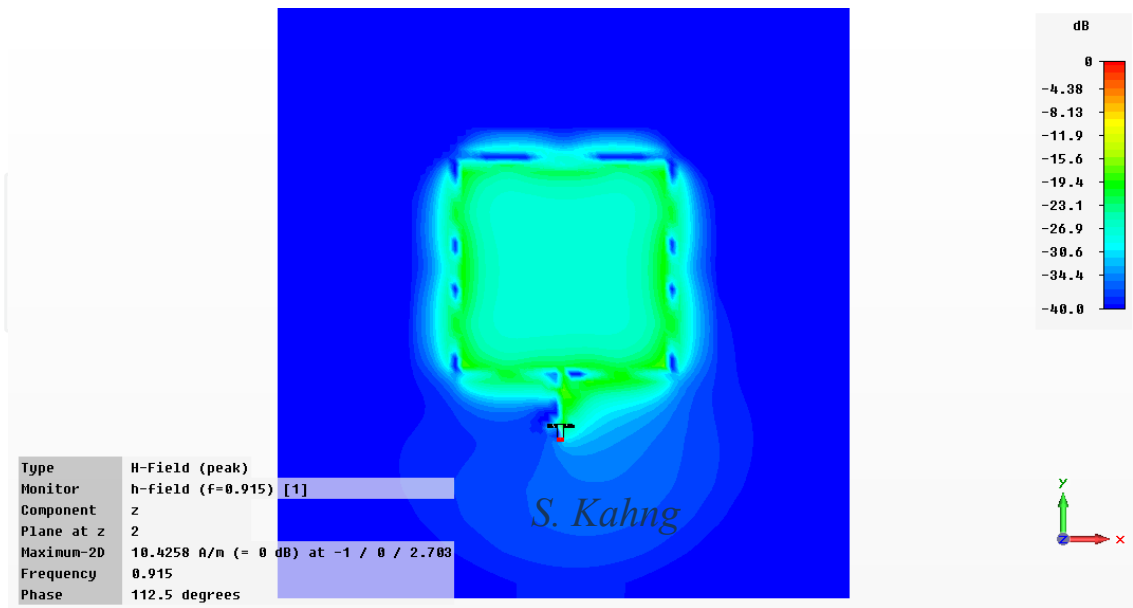


Fig. 17. Magnetic field distribution in the vicinity of the MTM ZOR loop.

The center axis passing through the loop has the maximum and almost uniform distribution of the magnetic field which will help the energy transfer enhanced. Using the new loops, we can check the transfer coefficient of the WPT with different distances. The following set-up has MTM ZOR loops placed with a 5cm-distance.

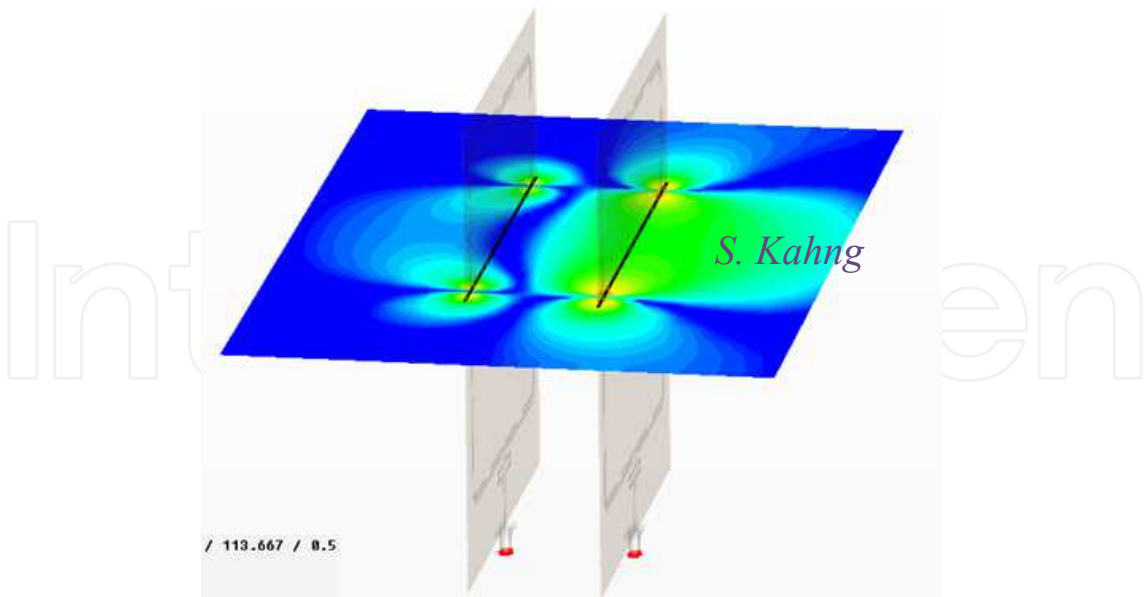


Fig. 18. The two MTM ZOR loops are 5cm away.

Though their distance is very short and serious impedance mismatch occurs, the original MTM ZOR loops are neither modified nor tuned for the best condition, for the sake of convenience. Its S_{21} as the transfer coefficient is calculated as

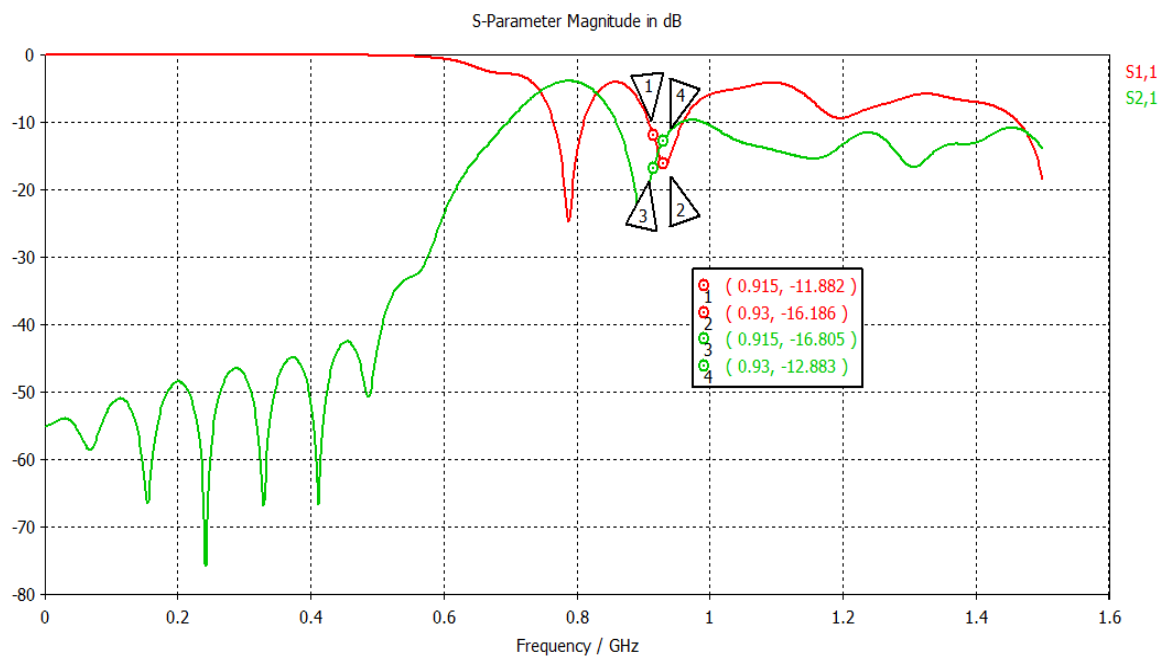


Fig. 19. S_{21} when the two MTM ZOR loops are 5cm away.

S_{21} at 900MHz reads -12dB with the unchanged loops in a changed environment. Actually, it is admitted that the MTM ZOR loop is not much superior to the conventional case for the near-field reactive ranges. Next, the distance between the MTM ZOR loops becomes 10cm.

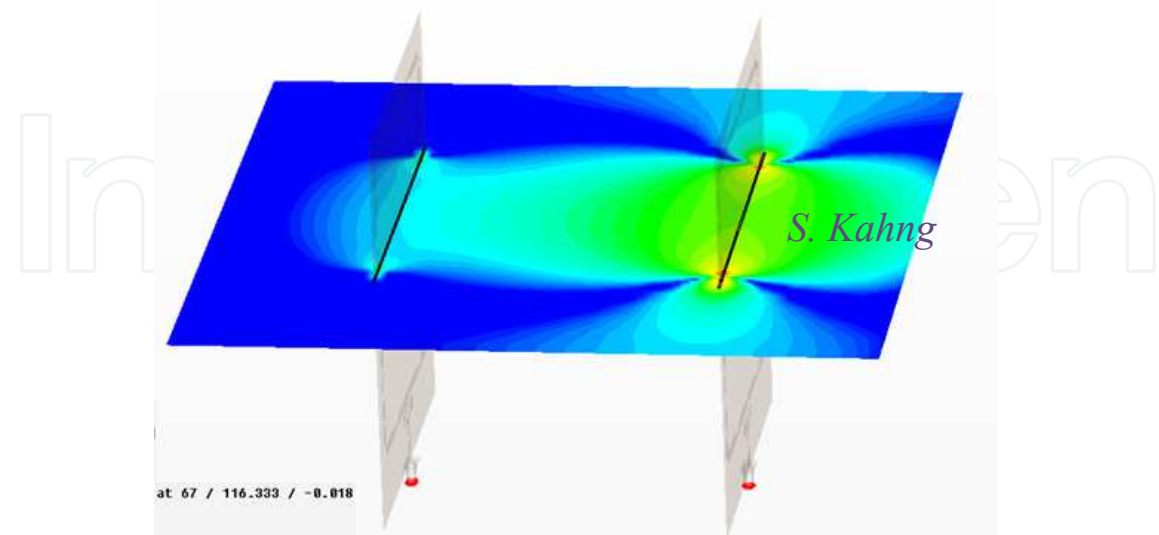


Fig. 20. The two MTM ZOR loops are 10cm away.
Still, the frequency of 900MHz is observed.

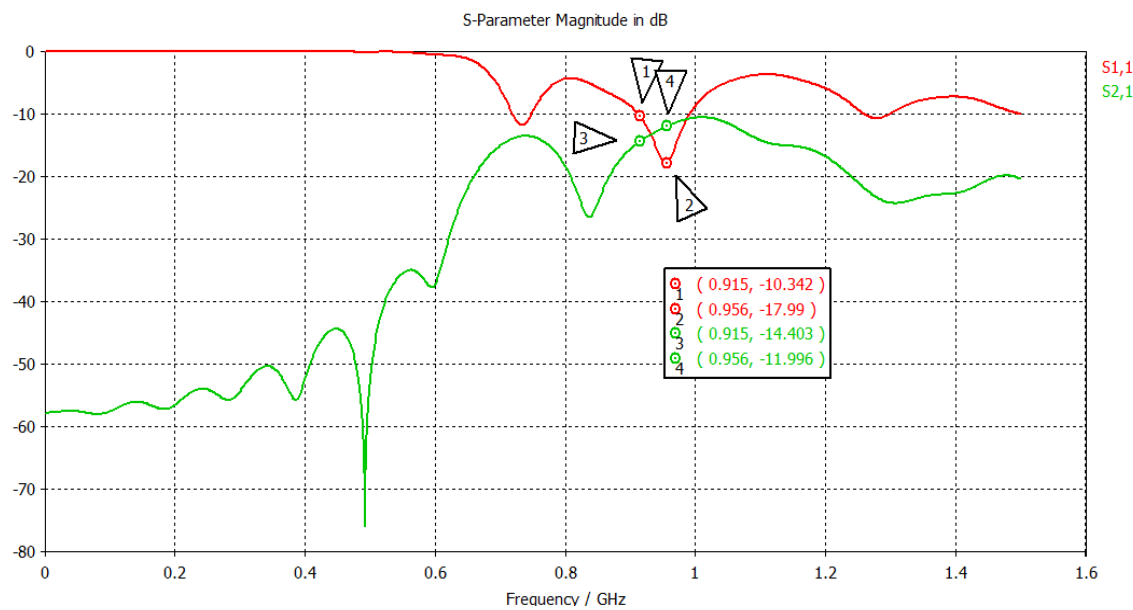


Fig. 21. S_{21} when the two MTM ZOR loops are 10cm away.

S_{21} at 900MHz reads approximately the same as the 5cm-case with the unchanged loops in a changed environment. It is good to see the transfer coefficient keep constant with the increased distance, which can't be expected in the conventional case. Next, the MTM ZOR loops are placed with the distance of 25cm.

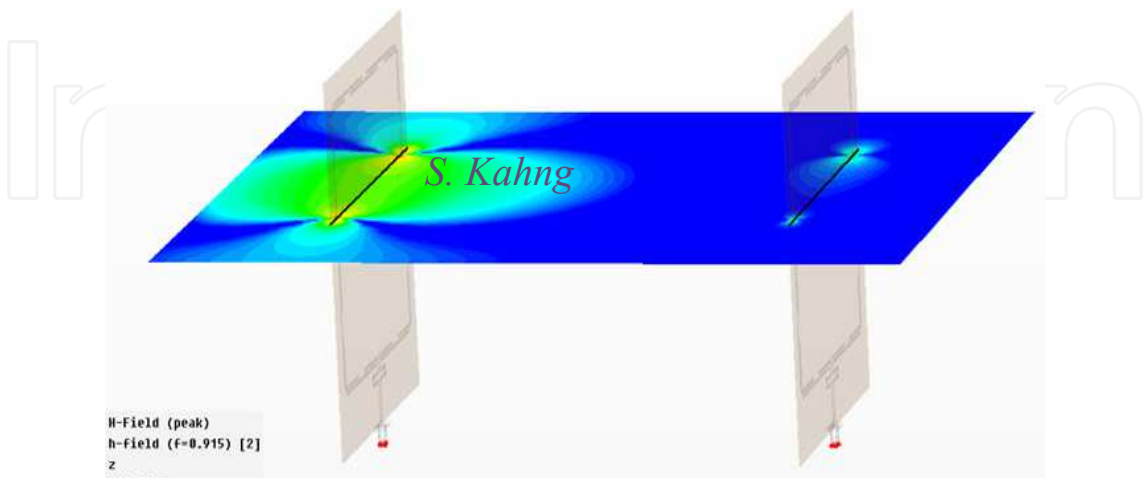


Fig. 22. S_{21} when the two MTM ZOR loops are 25cm away.

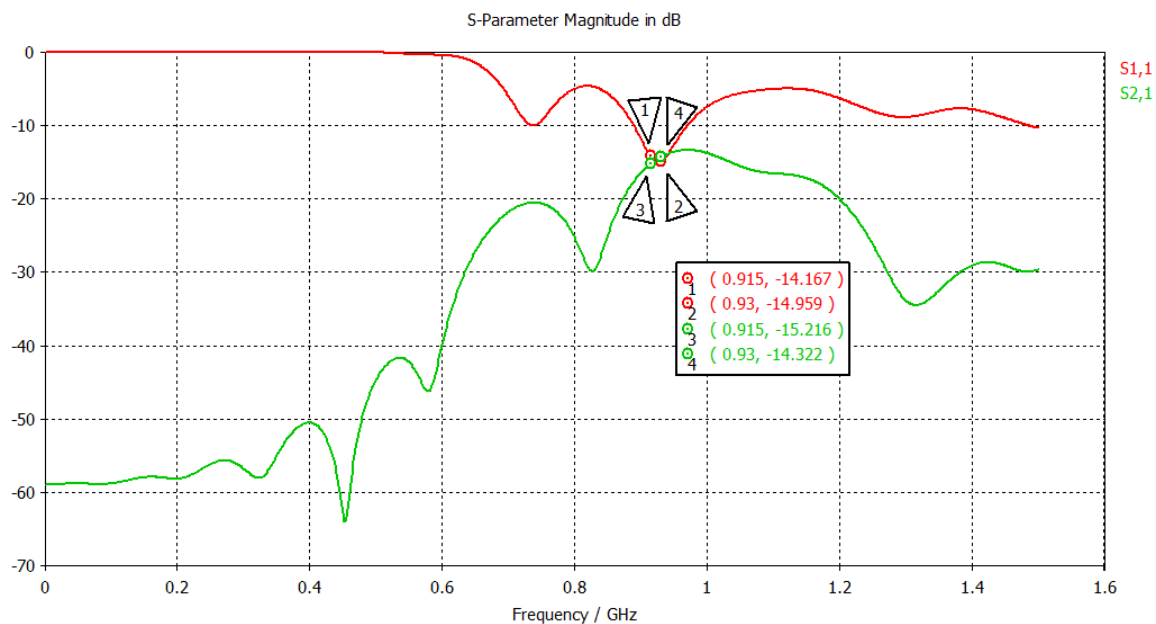


Fig. 23. S_{21} when the two MTM ZOR loops are 25cm away.

S_{21} at 900MHz reads -14dB with the unchanged loops in a changed environment. The transfer coefficient has dropped by the increased distance, but the MTM ZOR loops have better energy transfer efficiency than the conventional design method, while they have the same area of the loop. We have investigated the advantages of the new structure and the shortcomings of the conventional loops based upon the full-wave simulation approach. This is summarized with the following comparative data.

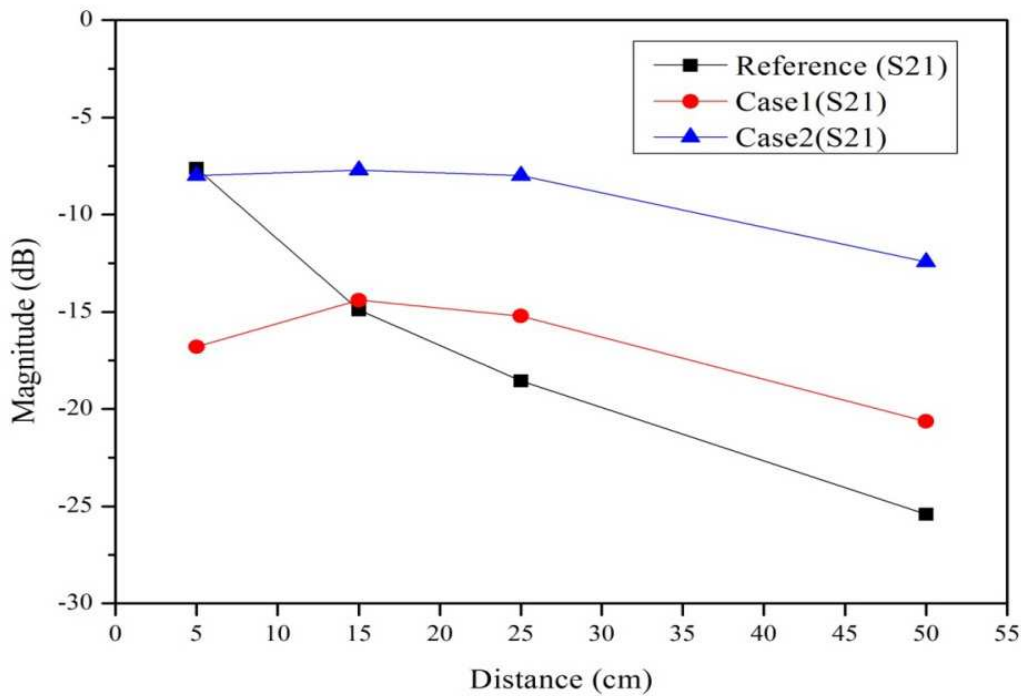


Fig. 24. Proposed technique(Case 1) and its modification(Case 2) compared to the conventional WPT.

The reference, case 1 and case 2 mean the conventional loops, the MTM ZOR loops and the reflector-backed MTM ZOR loops, respectively. My research group, maintaining the maximum magnetic field around the center axis due to the MTM ZOR, wanted to enhance the coupling and added and adjusted the reflectors to back the MTM ZOR WPT system which turns out the best in this experiment.

4. Conclusion

The necessity and background of the WPT was briefly tapped into, and two design schemes to make WPT systems were addressed. The design schemes are based on the circuit theory and the full-wave simulation. The circuit theory is used to obtain the initial and deterministic design parameters of the WPT system comprising resonators and their coupling elements and achieve a passband at the frequency of interest. The near-field RFID inspired full-wave simulation approach is to characterize EM fields of transmitter and receiver loops and their coupling, which is fed back to the design and get a right result. Going further from one method, hybridizing the two methods works well and several examples were presented. In particular, one of them is the enhanced efficiency of the WPT devising MTM ZOR loop by my research group.

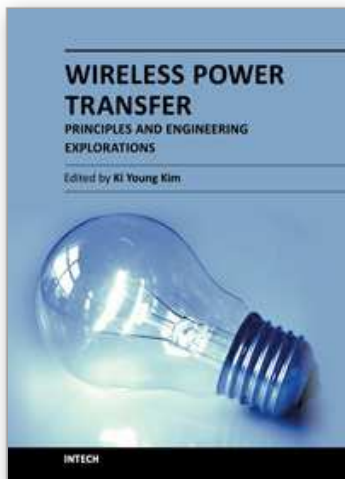
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